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FURTHER CONSIDERATION ON THE DESIGN OF A FOA CRYPTO-STEADY ENERGY SEPARATOR FOR USE IN SUPERSONIC AIRCRAFT

David Sobel, et al

George Washington University

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FURTHER CONSIDERATIONS ON THE DESIGN OF A FOA CRYPTOSTEADY ENERGY SEPARATOR FOR USE IN SUPERSONIC AIRCRAFT

by

David Sobel

and

Arshad Nawaz

School of Engineering and Applied Science
The George Washington University
Washington, D.C. 20006

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ABSTRACT

It is shown in this report that a fixed geometry Foa Energy Separator can satisfy the cooling requirements of the F-8U Aircraft without an external heat exchanger or staged configuration. A possible solution involves a hot to cold side nozzle area ratio of 0.283, dual pre-rotation at one half the rotor speed, and regenerative precooling at the Energy Separator entrance.

NOMENCLATURE

$\vec{c}$ = fluid particle velocity in F_s (Frame of reference in which flow is stationary)

h^o = specific stagnation enthalpy in F_u (Laboratory frame of reference)

$\dot{m}$ = mass flow rate

M = flight-Mach number

p = static pressure

p^o = stagnation pressure in F_u

R = universal gas constant

T = static temperature

T^o = stagnation temperature in F_u

u = particle velocity in F_u

u' = prerotation velocity

V = rotor peripheral velocity

α_b/α_a = ratio of total nozzle exit area on the hot side to total nozzle exit area on the cold side

γ = ratio of a specific heats

δ = $\cos\theta$ (negative on cold side)

η = nozzle efficiency

θ = angle $(\vec{V},-\vec{c})$

μ = mass flow ratio = $\dot{m}_b/\dot{m}_a$

ν = cold fraction = $\dot{m}_a/\dot{m}_i$

ρ = density

Subscripts

a = cold side

atm = atmospheric conditions

b = hot side

c = conditions leaving cooled spaces

d = discharge condition

i = energy separator inlet flow

o = conditions resulting from isentropic discharge from p_i^o to p_d

INTRODUCTION

In the analysis presented in Report TR-ES-724 [Ref. (1)], it was found that in the absence of prerotation, sufficiently low temperatures could be obtained in most, but not all, operating modes of the F-8U Aircraft. The purpose of this report is to show that, with the use of prerotation, the cooling requirements can be satisfied in all cases by a fixed geometry Energy Separator, utilizing engine bleed or ram air as input and maintaining atmospheric discharge pressures.

ANALYSIS

As in Report TR-ES-724, the operating conditions stipulated in the Hamilton Standard Report 1034 (12/10/53) are considered in this analysis. They are:

Table I. Specified F-8U Aircraft Operating Conditions

			BLEED		STANDARD ATMOS.	
CASE	ALTITUDE (FT)	OPERATING MODE	STAGNATION PRESS.(PSI)	STAGNATION TEMP.(°R)	STATIC PRESS(PSI)	STATIC TEMP(°R)
1	0	Max.speed/lvl.	197.1	1275	14.7	518.7
2	0	Loiter	48.6	710	14.7	518.7
3	0	Idle letdown	23.9	555	14.7	518.7
4	10,000	Max.speed/lvl wings press.	181.9	1279	10.11	483.0
5	10,000	Max. speed/lvl.	183.2	1279	10.11	483.0
6	10,000	Loiter	45.7	750	10.11	483.0
7	10,000	Idle letdown	19.46	585	10.11	483.0
8	23,000	Max.speed/lvl.	141.7	1230	5.95	436.7
9	25,000	Idle letdown	15.8	615	5.45	429.5
10	35,000	Max.speed/lvl. wings press.	124.0	1250	3.46	393.9
11	35,000	Max.speed/lvl.	124.5	1250	3.46	393.9
12	35,000	Loiter	31.6	755	3.46	393.9
13	35,000	Idle letdown	15.9	650	3.46	393.9
14	45,000	Cruise	33.7	985	2.14	390.0
15	51,500	Loiter	25.3	885	1.57	390.0
16	57,500	Max.speed/lvl.	19.2	1040	1.17	390.0
17	57,500	Idle letdown	17.3	800	1.17	390.0

The requirement of this preliminary design is to obtain a cold side output temperature not exceeding 520°R, while maintaining a cockpit pressure of no less than 8 psi[1], with the design restriction of a maximum rotor peripheral velocity of 1750 fps. Throughout this analysis the following is assumed: atmospheric hot and cold

[1] All pressures are in psia.

side discharge pressures, nozzle efficiencies on the cold side of 0.90 (η_a = 0.90) and on the hot side of 0.80 (η_b = 0.80), nozzle inclinations of 18° ($\delta = \cos\theta = \delta_b = -\delta_a = 0.95$), equal rotor peripheral velocities on the hot and cold sides ($V_a = V_b = V$), and dual prerotation at $\pm$ 0.5V.

The potential merit of prerotation has been discussed in Reference 3. A remarkably simple yet ingenious method of providing dual prerotation (positive on the cold side and negative on the hot side) was designed by Dr. Foa. Referring to the photograph of a model (Fig. 1), the helix is fixed to both the inner and outer cylinders. Inlet air enters (vertically upward in the photograph) and is divided on either side of the helix to provide dual prerotation as shown by the arrows. The rotors containing the hot and cold side nozzles are rigidly mounted on a common, free-spinning shaft.

Excessively high bleed air temperatures in many cases make it desirable to precool the engine bleed air before it enters the Energy Separator. One possible method of accomplishing this is shown schematically in Fig. 2. The air leaving the cooled spaces is still sufficiently cold (assumed to be 540°R) to be utilized in the counterflow exposure arrangement to precool the bleed air. The hot flow emerging from the Separator is high energy flow and is fed back to the engine. The cold flow is discharged at atmospheric pressure and is used to cool both equipment and cockpit. However, at high altitudes the discharge pressure (atmospheric) is too low to meet the 8 psi cockpit

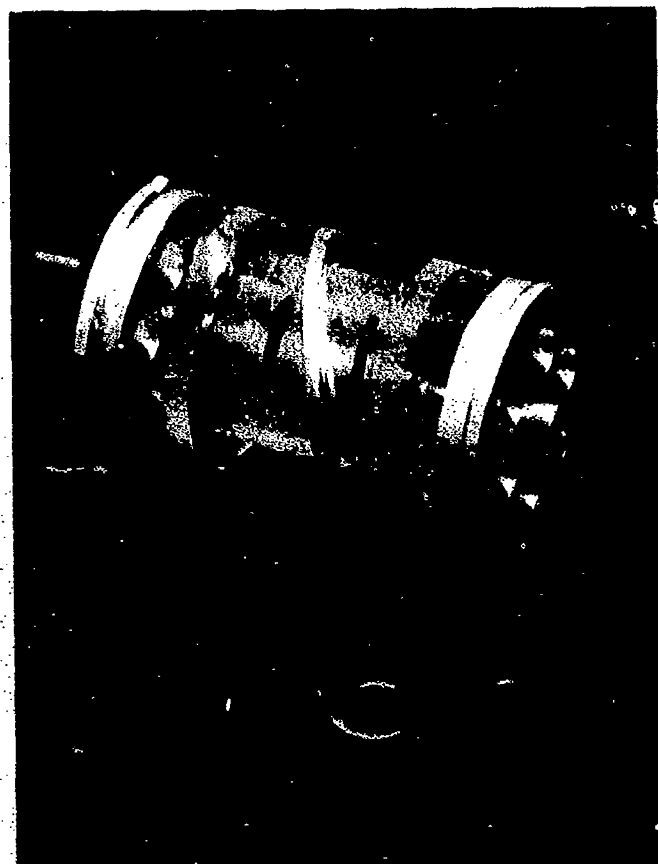

FIGURE 1

MODEL OF THE FOA ENERGY SEPARATOR USING HELIX TO PRODUCE DUAL PREROTATION

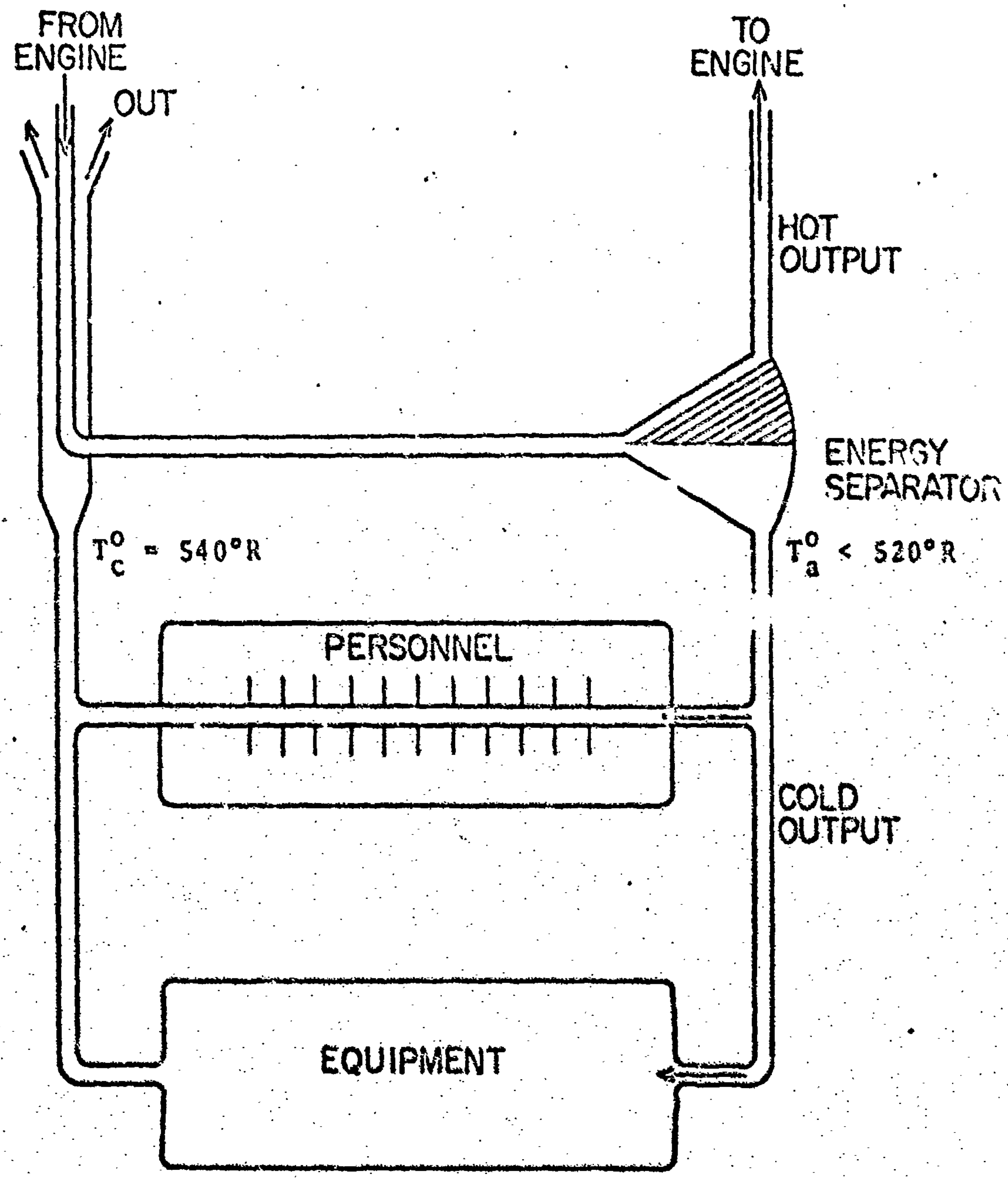
FROM
ENGINE
OUT
TO
ENGINE
HOT
OUTPUT
ENERGY
SEPARATOR
$T_c^o = 540°R$
$T_a^o < 520°R$
PERSONNEL
COLD
OUTPUT
EQUIPMENT

FIGURE 2

pressure requirement. To meet this requirement, the cold output, while cooling the equipment by means of through-flow air, is made to cool independently pressurized, recirculating air through a heat exchanger in the cockpit.

The effectiveness of the precooling counterflow arrangement is assumed to be 0.75. The Separator inlet temperature can then be calculated as:

$$T_i^o = T_{bleed}^o - .75\ (T_{bleed}^o - T_c^o)\nu \tag{1}$$

where

$$\nu = \dot{m}_a/\dot{m}_i$$

The equations governing the performance of the Foa Energy Separator are presented below. Derivations may be found in References (2) and (3).

The fluid particle velocity resulting from an isentropic discharge is found on both hot and cold sides as:

$$u_o = \sqrt{2h_i^o[1-(p_d/p_i^o)^{(\gamma-1/\gamma)}]} \tag{2}$$

and the temperature increment on each side is

$$T_d^o - T_i^o = \frac{V^2}{6000}\left(-\frac{u'}{V} + 1 + \delta\left[n\left(\frac{u_o^2}{V^2} + 1 - 2\frac{u'}{V}\right)\right]^{1/2}\right). \tag{3}$$

By definition the mass flow ratio is

$$\mu = \frac{\dot{m}_b}{\dot{m}_a} = \frac{1-\nu}{\nu} \tag{4}$$

The above equations apply to both the internal and external separation configurations of the Foa Energy Separator. As this report deals with the design of an internal separation device, where the governing design parameter is the nozzle area ratio α_b/α_- the following relations become essential [Ref. 3]: On both sides, the fluid particle velocity, c, in F_s, and the density ρ, can be found as;

$$c = \sqrt{\eta(V^2-2u'V+u_o^2)} \tag{5}$$

and

$$\rho = \rho_i^o \frac{p_d/p_i^o}{1-\eta[1-(p_d/p_i^o)^{\gamma-1/\gamma}] + (1-\eta)\frac{V^2}{2h_i^o}(1-2\frac{u'}{V})} \tag{6}$$

ρ_i^o can be determined by the perfect gas law as

$$\rho_i^o = p_i^o/RT_i^o$$

and the mass flow ratio μ, can be more conveniently written as

$$\mu = \frac{u_a'+c_a\delta-V}{V-u_b'+c_b\delta} \tag{7}$$

where c is found from Equation (5).

Finally, the nozzle area ratio α_b/α_a, is

$$\alpha_b/\alpha_a = \mu\frac{c_a}{c_b}\frac{\rho_a}{\rho_b} \tag{8}$$

where c, ρ, and μ are found from Equations (5), (6) and (7) respectively.

The solution to the above equations requires an iterative procedure. The specified parameters are; inlet pressure (p_i^o), discharge pressures ($p_{da} = p_{db} = p_{atm}$) and the magnitude of prerotation ($u_a' = -u_b' = 0.5V$). The cold fraction (ν) is varied, allowing the computation of the inlet temperature (T_i^o) from Equation (1) and the mass flow ratio (μ) from Equation (4). For the stipulated prerotation magnitude, Equation (7) may be written as

$$V^2\left[2 - \frac{(1.5\mu + 0.5)^2}{\mu^2\delta^2\eta_b}\right] + V\left[\frac{2\sqrt{\eta_a}\,u_{oa}(1.5\mu + 0.5)}{\mu^2\delta\eta_b}\right] + \left[\frac{\eta_a u_{oa}^2}{\eta_b\mu^2} + u_{ob}^2\right] = 0 \qquad (9)$$

Thus the rotor peripheral velocity (V) may be calculated. Finally, the discharge temperatures and nozzle area ratio can be computed from Equations (3) and (8) for a given cold fraction. The computations were executed and printed out by computer. For each case, the cooling requirements could be satisfied by a number of area ratios. As it is desirable to have a fixed geometry Separator, a single area ratio satisfying the requirements for all cases was sought. The results for one such area ratio are displayed in Table II.

TABLE II: PERFORMANCE USING BLEED AIR

$\alpha_b/\alpha_a = 0.283$

$p_{db} = p_{da} = p_{atm}$

$u_a' = -u_b' = 0.5V$

Case	$\dot{m}_a/\dot{m}_i$	T^o_{Bleed} (°R)	T^o_i (°R)	p^o_i (PSI)	V (fps)	T^o_a (°R)	T^o_b (°R)
1	0.779	1275	846	197.1	1443	520	1995
2	0.760	710	613	48.6	833	488	1008
3	0.753	555	547	23.9	509	498	695
4	0.783	1279	845	181.9	1523	492	2118
5				same as 4			
6	0.764	750	630	45.7	948	473	1137
7	0.755	585	560	19.5	597	493	764
8	0.788	1230	822	141.7	1583	455	2189
9	0.759	615	572	15.8	763	467	904
10	0.795	1250	826	124.0	1700	424	2389
11				same as 10			
12	0.773	755	630	31.6	1145	416	1361
13	0.764	650	587	15.9	918	440	1064
14	0.781	985	724	33.7	1375	432	1766
15	0.782	885	683	25.4	1346	405	1679
16	0.782	1040	747	19.2	1409	442	1839
17	0.780	800	648	17.3	1284	391	1557

Thus, with an area ratio of 0.283, the cooling requirements can be satisfied in all cases using engine bleed air.

It is also of interest to investigate the possibility of using ram, rather than bleed, air. For any given altitude and flight Mach number, the stagnation temperature and pressure can be determined from

$$T^o = T_{atm}(1 + \frac{\gamma-1}{2} M^2_{F-8u}) \tag{10}$$

$$p^o = p_{atm}(1 + \frac{\gamma-1}{2} M^2_{F-8u})^{\frac{\gamma}{\gamma-1}} \tag{11}$$

Assuming the flow to be adiabatic and isoenergetic, $T^o_{ram} = T^o$. To account for pressure losses a stagnation pressure ratio, p^o_{ram}/p^o, of 0.85 was stipulated. The ram air was then used in place of the engine bleed air in Fig. 2. The calculation procedure to determine the performance was then identical to that for bleed air. The results for the same area ratio (0.283) are displayed in the Appendix, for the maximum speed conditions listed in Table 1. As the flight Mach numbers in these cases were not known, they were assumed to be between Mach 2.0 and Mach 3.0. It is seen from these tables that the cooling requirements can also be satisfied using ram air.

In a few cases the rotor peripheral velocity approaches the 1750 fps design limit. However, the cold side output temperatures in these cases are so low that reduction of the rotor peripheral velocity could be achieved by throttling the cold output, while still maintaining cold output temperatures well below 520°R.

CONCLUSIONS

This report has shown that the Foa Energy Separator, with prerotation, can satisfy the specified cooling requirements of aircraft similar to the F-8U, using either bleed or ram air.

It is felt that the Energy Separator configuration (Fig. 2) discussed in this report could be improved through further analysis. For instance, reduced cold side discharge pressure, the merits of which were discussed in Ref. 1, could be used to increase performance. A simple method of maintaining a low discharge pressure would be to have the hot flow (primary) drive the cold flow (secondary) in an ejector pump arrangement.

REFERENCES

1. Sobel, D. and Nawaz, A., "Preliminary Design of a Foa Cryptosteady Energy Separator for Use in Supersonic Aircraft," The George Washington University Technical Report TR-ES-724, September 1972.

2. Foa, J. V., "Energy Separator," Rensselaer Polytechnic Institute, Troy, New York, Technical Report TR-AE-6401, January 1964.

3. Foa, J. V., "Performance of the Cryptosteady-Flow Energy Separator," The George Washington University Technical Report TR-ES-722, July 1972.

APPENDIX:

PERFORMANCE OF THE FOA ENERGY SEPARATOR USING RAM AIR

$\alpha_b/\alpha_a = 0.283$

$p_{da} = p_{db} = p_{atm}$

$u_a' = -u_b' = 0.5V$

$p_i^o = 0.85\ p_{ram}^o$

Altitude = 0 ft.

M	$\dot{m}_a/\dot{m}_i$	T_{ram}^o (°R)	T_i^o (°R)	p_i^o (psi)	V (fps)	T_a^o (°R)	T_b^o (°R)
2.0	0.769	934	707	97.8	1124	494	1415
2.1	0.771	977	724	114.3	1183	492	1506
2.2	0.773	1021	742	133.6	1242	490	1601
2.3	0.775	1068	761	156.0	1301	488	1701
2.4	0.778	1117	780	183.0	1366	486	1812
2.5	0.780	1168	801	213.5	1425	485	1920
2.6	0.782	1221	823	249.3	1484	484	2033
2.7	0.785	1276	843	290.9	1551	482	2160
2.8	0.787	1333	865	339.1	1611	481	2282
2.9	0.790	1392	887	394.8	1679	480	2420
3.0	0.792	1453	911	459.0	1740	480	2553

$\alpha_b/\alpha_a = 0.283$

$p_{da} = p_{db} = p_{atm}$

$u_a' = -u_b' = 0.5V$

$p_i^o = 0.85\ p_{ram}^o$

Altitude = 10,000 ft.

M	$\dot{m}_a/\dot{m}_i$	T_{ram}^o (°R)	T_i^o (°R)	p_i^o (psi)	V (fps)	T_a^o (°R)	T_b^o (°R)
2.0	0.769	869	679	67.2	1102	475	1360
2.1	0.771	909	696	78.6	1159	473	1446
2.2	0.773	951	713	91.9	1216	470	1537
2.3	0.775	994	730	107.4	1274	469	1631
2.4	0.778	1039	748	125.6	1337	466	1737
2.5	0.780	1087	767	146.8	1395	464	1839
2.6	0.782	1136	787	171.4	1453	463	1946
2.7	0.785	1187	806	200.0	1517	461	2066
2.8	0.787	1240	827	233.1	1576	460	2182
2.9	0.790	1295	848	271.4	1641	458	2313
3.0	0.792	1352	870	315.6	1701	458	2438

$\alpha_b/\alpha_a = 0.283$
$p_{da} = p_{db} = p_{atm}$
$u_a' = -u_b' = 0.5V$
$p_i^o = 0.85\ p_{ram}^o$

Altitude = 23,000 ft.

M	$\dot{m}_a/\dot{m}_i$	T_{ram}^o (°R)	T_i^o (°R)	p_i^o (psi)	V (fps)	T_a^o (°R)	T_b^o (°R)
2.0	0.769	787	644	39.5	1073	451	1290
2.1	0.771	822	659	46.2	1128	448	1371
2.2	0.773	860	675	54.0	1184	445	1455
2.3	0.775	899	691	63.2	1238	443	1543
2.4	0.778	940	707	73.9	1300	440	1641
2.5	0.780	983	724	86.4	1355	438	1736
2.6	0.782	1028	742	100.9	1411	437	1836
2.7	0.785	1074	760	117.7	1473	435	1947
2.8	0.787	1122	779	137.2	1529	433	2054
2.9	0.790	1172	798	159.7	1592	431	2176
3.0	0.792	1224	818	185.7	1649	430	2292

$\alpha_b/\alpha_a = 0.283$

$p_{da} = p_{db} = p_{atm}$

$u_a' = -u_b' = 0.5V$

$p_i^o = 0.85\ p_{ram}^o$

Altitude = 25,000 ft.

M	$\dot{m}_a/\dot{m}_i$	T_{ram}^o (°R)	T_i^o (°R)	p_i^o (psi)	V (fps)	T_a^o (°R)	T_b^o (°R)
2.0	0.769	774	639	36.3	1068	447	1279
2.1	0.771	809	654	42.4	1124	444	1359
2.2	0.773	846	669	49.6	1178	442	1442
2.3	0.775	885	684	58.0	1233	439	1529
2.4	0.778	925	701	67.8	1294	436	1626
2.5	0.780	968	717	79.2	1349	434	1721
2.6	0.782	1011	735	92.5	1404	433	1819
2.7	0.785	1057	753	107.9	1466	430	1929
2.8	0.787	1104	771	125.8	1522	429	2035
2.9	0.790	1153	790	146.5	1584	427	2155
3.0	0.792	1204	810	170.3	1641	426	2269

$\alpha_b/\alpha_a = 0.283$
$p_{da} = p_{db} = p_{atm}$
$u_a' = -u_b' = 0.5V$
$p_i^o = 0.85\ p_{ram}^o$

Altitude 35,000 ft.

M	$\dot{m}_a/\dot{m}_i$	T_{ram}^o (°R)	T_i^o (°R)	p_i^o (psi)	V (fps)	T_a^o (°R)	T_b^o (°R)
2.0	0.769	709	612	23.0	1045	428	1224
2.1	0.771	742	625	26.9	1099	425	1300
2.2	0.773	775	639	31.4	1152	422	1378
2.3	0.775	811	653	36.8	1205	419	1460
2.4	0.778	848	668	43.0	1264	416	1551
2.5	0.780	887	684	50.2	1317	414	1640
2.6	0.782	927	700	58.7	1370	412	1732
2.7	0.785	969	716	68.4	1430	410	1836
2.8	0.787	1012	733	79.8	1484	408	1935
2.9	0.790	1057	751	92.9	1544	406	2047
3.0	0.792	1103	769	108.0	1599	405	2155

$\alpha_b/\alpha_a = 0.283$

$p_{da} = p_{db} = p_{atm}$

$u_a' = -u_b' = 0.5V$

$p_i^o = 0.85\ p_{ram}^o$

Altitude = 45,000 ft.

M	$\dot{m}_a/\dot{m}_i$	T_{ram}^o (°R)	T_i^o (°R)	p_i^o (psi)	V (fps)	T_a^o (°R)	T_b^o (°R)
2.0	0.769	702	609	14.2	1043	426	1218
2.1	0.771	734	622	16.6	1096	423	1293
2.2	0.773	768	636	19.4	1149	420	1371
2.3	0.775	803	650	22.7	1202	417	1452
2.4	0.778	839	665	26.6	1260	414	1543
2.5	0.780	878	680	31.1	1313	412	1631
2.6	0.782	917	696	36.3	1360	410	1722
2.7	0.785	959	712	42.3	1426	407	1825
2.8	0.787	1002	729	49.3	1479	406	1924
2.9	0.790	1046	746	57.4	1540	404	2035
3.0	0.792	1092	764	66.8	1594	402	2142

$\alpha_b/\alpha_a = 0.283$

$p_{da} = p_{db} = p_{atm}$

$u_a' = -u_b' = 0.5V$

$p_i^o = 0.85\ p_{ram}^o$

Altitude = 51,500 ft.

M	$\dot{m}_a/\dot{m}_i$	T_{ram}^o (°R)	T_i^o (°R)	p_i^o (psi)	V (fps)	T_a^o (°R)	T_b^o (°R)
2.0	0.769	702	609	10.4	1043	426	1218
2.1	0.771	734	622	12.2	1096	423	1293
2.2	0.773	768	636	14.2	1149	420	1371
2.3	0.775	803	650	16.6	1202	417	1452
2.4	0.778	839	665	19.5	1260	414	1543
2.5	0.780	878	680	22.7	1313	412	1631
2.6	0.782	917	696	26.6	1366	410	1722
2.7	0.785	959	712	31.0	1426	407	1825
2.8	0.787	1002	729	36.1	1479	406	1924
2.9	0.790	1046	746	42.0	1540	404	2035
3.0	0.792	1092	764	48.9	1594	402	2142

$\alpha_b/\alpha_a = 0.283$
$p_{da} = p_{db} = p_{atm}$
$u_a' = -u_b' = 0.5V$
$p_i^o = 0.85\ p_{ram}^o$

Altitude = 57,500 ft.

M	$\dot{m}_a/\dot{m}_i$	T_{ram}^o (°R)	T_i^o (°R)	p_i^o (psi)	V (fps)	T_a^o (°R)	T_b^o (°R)
2.0	0.769	702	609	7.8	1043	426	1218
2.1	0.771	734	622	9.1	1096	423	1293
2.2	0.773	768	636	10.7	1149	420	1371
2.3	0.775	803	650	12.5	1202	417	1452
2.4	0.778	839	665	14.6	1260	414	1543
2.5	0.780	878	680	17.0	1313	412	1631
2.6	0.782	917	696	19.9	1366	410	1722
2.7	0.785	959	712	23.2	1426	407	1825
2.8	0.787	1002	729	27.1	1479	406	1924
2.9	0.790	1046	746	31.5	1540	404	2035
3.0	0.792	1092	764	36.6	1594	402	2142